

Green tribology: Fundamentals and future development

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Abstract: As green tribology is a new field of tribology still in its infancy, understanding its fundamentals is essential for its further development. In this article, a brief historical retrospective on the emergence of green tribology is introduced first, and then the definition, objectives, and disciplinary features of green tribology are clarified. In particular, the technological connotations of green tribology are expounded comprehensively. Also, the developing directions of this new area are envisaged. These findings may contribute to laying the foundation of further advancement in green tribology.

Keywords: green tribology; technological connotations; environmental impact; biological impact; developing directions

1 Background

Since the 1980s, energy and environmental problems on a global scale have increased in severity year by year. Against this background, the objectives of tribology expanded gradually, and then some tribologists successively put forward several new notions: “tribology for energy conservation” (1997), “environmental friendly tribology” (2000), and “ecological tribology or ecotribology” (2000). In particular, after entering the new millennium, tribology was expected to have an increasingly important role to play along with the crises of resources, energy, and environment being aggravated in the world. Its basic objectives of “controlling friction, reducing wear, and improving lubrication” have extended to “saving energy and materials, reducing emissions, shock absorption, decreasing noise pollution, developing bio- and ecolubrication and improving quality of life.” It is noticeable that tribology has developed into a new phase. In 2001, to mirror this change in objectives of

tribology, a term/area “green tribology” was advanced by the present author at a national symposium on tribology in China. A paper was published from this conference [1], in which the concept and objectives of green tribology were clarified. Soon after, another two expressions also emerged successively, namely, “total tribology” (2001–2002) and “lifecycle tribology” (2004).

In 2008, the concept of green tribology was raised again by the present author at the 5th China International Symposium on Tribology in a plenary lecture, which was intended to replace similar notions as mentioned above [2]. In the lecture, an investigation of the industrial application of tribology in China was presented. It was found that the industrial enterprises of the whole nation can save 414.8 hundred million USD per year (a lowest figure selected) (1.55% of gross national product, GNP, 2006) by means of the industrial application of tribology. Just based on this investigation, it was concluded that “making tribology green”/green tribology is now able to provide full technical support to the preservation of resources and energy, environmental protection, and improvement of quality of life, and even to reduce natural disasters, and so it is certainly an important way forward to a

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sustainable society [2]. This lecture had every attention of Professor Jost.

In the following year, Jost promoted the Chinese Tribology Delegation's visit to the UK and suggested that the subject of this visit be green tribology: saving energy and materials, improving the environment and the quality of life [3]. During this visit, a keynote address was delivered by the present author, in which the definition, major tasks, and main contents of green tribology were explained. Moreover, the view that "green" embodies an ideology, sense, and values was advanced [4]. In this very period, after repeated deliberating with Jost, an exact definition of green tribology was determined.

Soon after, Jost delivered an opening address under the distinct title of "Green Tribology—A footprint where economies and environment meet" at the Fourth World Tribology Congress in Kyoto. He introduced the definition and main objectives of green tribology, and indicated that the expression "green tribology" was first used by Professor Si-weir Zhang about 2 years previously and was launched as a tribology policy in London on June 8 of the same year. This date can be regarded as the acknowledged birthday of green tribology as an international concept [5]. It has since spread rapidly and has become an integral part of tribology in several major countries [6]. The above is a brief historical retrospective on the emergence of green tribology.

In recent years, a number of papers, academic books, and reports related to this area have been presented [1, 6–12]. However, up to now, there have been few articles expounding the concepts, objectives, disciplinary features, and technological connotations of green tribology in precise terms and in an all-round way. As green tribology is a new field of tribology still in its infancy, an exact understanding of its fundamentals is essential for further development. Connected with this, the aim of this current work is to clarify the fundamental basics and the developing directions of green tribology based on the analysis, generalization, and summation of the research achievements of green tribology, but it is not intended to review progress in this new field.

2 Concepts, definition, and objectives

The basic objectives of tribology are "controlling friction, reducing wear, and improving lubrication." Therefore, the saving of energy and materials is certainly one of the main objectives. Obviously, in this respect, tribology is much better able to meet the demands of a sustainable society. However, it did not consider the ecological balance and environmental impact at that time owing to the limitations of the times. Thereupon, green tribology emerged to keep abreast of the sustainable developments of nature and society. "Green" is meant as a new mode of thinking that represents views on ecological balance and environmental protection, and so embodies the ideology of the sustainable developments of nature and society perfectly. The main task of green tribology is to study and develop the tribological theories, methods, and technologies with the new mode of thinking and a completely new angle of view as stated above. Green tribology is defined as the science and technology of the tribological aspects of ecological balance and of environmental and biological impacts [3–5].

Green tribology might be regarded as a subdiscipline of tribology, such as nanotribology and biotribology. These subdisciplines are all within the general concept of tribology but place more emphasis on their specific characteristics. However, compared with the other subdisciplines of tribology, green tribology is an interdisciplinary subject intersected with a wide range of subjects, such as energy science, environmental science, ecology, science of materials, life science, geosciences, and green chemistry (environmental benign chemistry) [9].

In a broad sense, green tribology involves tribology for life (human biotribology), biomimetic tribology, renewable energy tribology, and a part of geotribology [9].

Guided by the viewpoint of sustainable development of resources and environment, the main objectives of green tribology are the environmental-friendly saving of energy and materials, and the enhancement of the environment and quality of life [3–5]. Thus, the concepts and objectives of green tribology might be summarized into 3L + 1H, namely, *low* energy consumption, *low* discharge (CO₂), *low* environmental

cost, and *high* quality of life. The mission of green tribology is researching and developing tribological technologies to reach the main objectives, thus making the sustained artificial ecosystems of the tribological parts and tribo-systems in the course of a lifecycle [9].

In view of this, green tribology is a subdiscipline of tribology mainly concerning the environmentally friendly consumption of resources and energy, and the environmental and biological impacts. Moreover, it is also an independent science and technology with definite disciplinary character, namely, researching and applying the tribological theories and technologies forward to a sustainable society and nature. Therefore, in a sense, green tribology could be defined as the science and technology of research on the tribological theories and technologies and the practices related to a sustainable society and nature, and might also be termed “tribology for sustainability” or “sustainable tribology.”

3 Technological connotations (research contents/areas)

3.1 Sustainable tribo-techniques for saving energy and materials, and increasing the lifetime of tribological parts and tribo-systems

3.1.1 Technologies for improving the fuel economy of engine systems

Environmental impact and energy consumption have made the improvement of the fuel economy of engine systems an important issue. For this purpose, a number of new lubricants were developed, such as PAO(Polyalpholefin)-based lubricants [13] and new types of synthetic esters [14].

In addition, DLC-Si coating with diesel fuel lubrication has a larger effect on friction reduction than coating with engine oil lubrication [15].

A super-low friction torque tapered roller bearing (TRB) applied to the rear axle differential for passenger cars was developed [16], which obtained a friction torque reduction of up to 75% compared with the conventional low friction torque TRB. Its three features are shown in Fig. 1.

A new nanoparticle-modified polyetheretherketone (PEEK) composite was used as the thin coating for

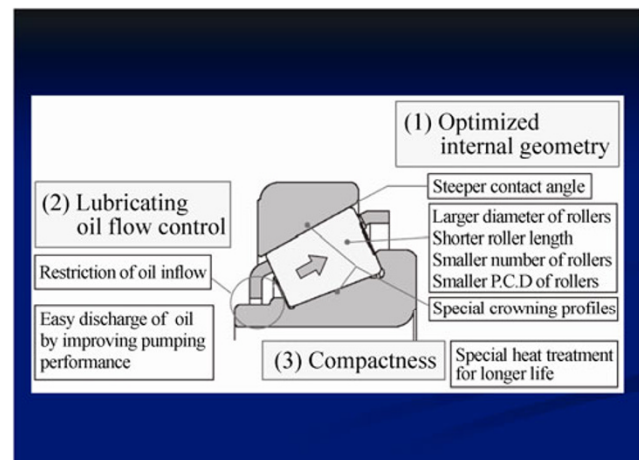


Fig. 1 Features of developed tapered roller bearing (TRB) [16].

hybrid bushings in automotive aggregates [17]. It exhibited a much lower coefficient of friction and specific wear rate in comparison to the commercial product, leading to a pronounced reduction in fuel consumption and a better engine efficiency.

3.1.2 Technologies for super-low friction and wear resistance

A novel fullerene-like hydrogenated carbon film was prepared by pulse bias-assisted plasma enhanced chemical vapor deposition, and its mechanical and tribological properties were investigated [18]. This film exhibited super-low friction and wear in both dry inert and humid ambient atmospheres and less sensitivity to H₂O and O₂ molecules in air.

The mechanism responsible for excellent tribological properties in AlMgB₁₄-TiB₂ nanocomposite coatings was identified as oxidation of the TiB₂ phase and subsequent reaction of the oxide with moisture to produce a surface layer of boric acid, B(OH)₃ [19]. These coatings show sustained friction coefficient values as low as 0.02 in water-glycol-based lubricants, and offer a unique combination of excellent wear resistance and low friction when combined with the high hardness of the mixed-phase composite (30–35 GPa).

The wear behaviors of ultra-high molecular weight polyethylene (UHMWPE) coated with hydrogenated diamond like carbon (DLCH) layers were investigated [20]. It was found that the surface hardness and the wear resistance of coated materials were increased compared to that of an uncoated one. The DLCH coatings could be a potential method to reduce backside wear in modular implants.

3.2 Sustainable tribo-techniques for removing or reducing the harmful effects on ecological balance (including human health) produced by both tribological parts and tribo-systems in the course of a lifecycle

3.2.1 Eco-/bio-lubricants

Environmental issues are leading to a growing interest in eco- and bio-lubricants. However, the perfect eco- and bio-lubricants should be eco-non-toxic and bio-degraded quickly, and moreover, capable of sustainable large-scale production.

SAPS (phosphorus and sulfur)-free additive KWF-012122 derived from natural resource “amino acids” was developed [21]. More recently, the use of chitin, chitosan, and acylated derivatives as thickener agents of vegetable oils has been explored [22].

Sliding friction was analyzed for titanium covered with mixed biofilms consisting of *Streptococcus mutans* and *Candida albicans* [23]. The structure of biofilms consisted of microbial cells, and their hydrated exopolymeric matrix acts as a lubricant. Very low friction was found on titanium immersed in artificial saliva and sliding against alumina in the presence of biofilms. This result is of particular significance for dental implant connections and prosthetic joints.

Hydration lubrication is a new area explored recently. Klein [24] pointed out that combining the supramolecular benefits of polymer brushes together with the highly hydrated nature of zwitterionic phosphorylcholine monomers could provide important advantages in designing extremely efficient boundary lubricants.

Recently, much research and the development of new bio-based metal working fluid based on various vegetable oils have been engaged. From the viewpoint of the qualities required of metal working fluids, the advantages and disadvantages of vegetable oils as lubricants were listed (Table 1) [25].

More recently, Winter and coworkers [26] described the use of ecologically benign lubricants as cutting fluid and hydraulic fluid. They analyzed the usability and resulting technological and ecological consequences of water miscible biopolymers as a substitute, and confirmed the good performance of the polymer fluid as an optimal ecologically benign lubricant for metal processing and hydraulic systems.

Table 1 Advantages and disadvantages of vegetable oils as lubricants [25].

Advantages	Disadvantages
High biodegradability	Low thermal stability
Low pollution of the environment	Low oxidative
Compatibility with additives	High freezing points
Low production cost	Poor corrosion protection
Wide production possibilities	
Low toxicity	
High flash points	
Low volatility	
High viscosity indices	

Tribological study and case analyses of the elastomeric bearings lubricated with seawater for marine propeller shaft systems were conducted [27].

3.2.2 Biomimetic tribological materials and tribo-techniques

As living beings have natural adaptability to ecological environments, biomimetic tribological materials and tribo-techniques became an important area of green tribology.

To obtain a much adhesive erosion-protection surface on the hydraulic construction (flood-way concrete structure), UHMWPE was applied as an erosion-resistant material under the condition of high sand-content slurry erosion, and a bionic surface structure based on the epidermis of sandfish and the clamp of a dragonfly’s wing was developed by Jian Li and Chengqing Yuan (Fig. 2). This technique has

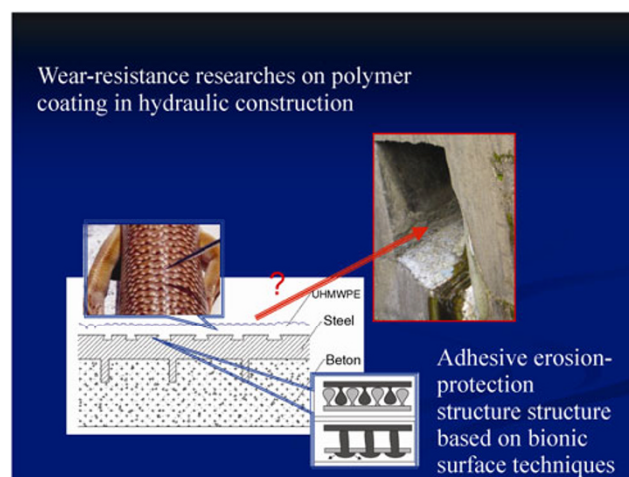


Fig. 2 Bionic surface structure based on the epidermis of sandfish and the clamp of dragonfly’s wing.

provided the concrete structure with good protection after three flood seasons (Personal communication, 2010).

More recently, the mechanisms of sand erosion resistance of the desert scorpion (*Androctonus australis*) were investigated to improve the erosion resistance of tribo-components [28]. It was found that the functional surfaces used for sand erosion resistance of the desert scorpion were constructed by the special micro-textures such as bumps and grooves.

3.2.3 Noise reduction

Brake squeal is a very complex phenomenon. There is as yet neither a complete understanding of the problem nor a generalized theory of squeal mechanism. Recently, an investigation on brake squeal noise was carried out on simplified experimental rigs [29]. It was concluded that a squeal-free design of a brake system should consider not only the out-of-plane dynamics but also the in-plane dynamics, and the role of damping must be thoroughly considered. Moreover, it was found that the stick-slip, detachment between disc and pad, and other nonlinear characteristics of the brake, did not affect the squeal propensity of the brake but played a relevant role on the amplitude of the radiated sound.

3.2.4 Application of lifecycle assessment (LCA) to tribological technologies

Recently, Bartz [30] advanced that the green automobile has to be green from the cradle to grave. This means that the lifecycle assessment (LCA) should be the required approach.

A procedure based on the digraph and matrix method was developed for modeling and evaluation of the LCA of a tribo-element [31]. This procedure is not only useful for the evaluation of LCA of tribo-elements at the operational stage, but can also be used for the design and development of tribo-elements at the system design stage from the viewpoint of LCA.

An environmental approach to environmentally friendly hydraulic fluid was conducted by Muller-Zermeni and Gaule [32]. They pointed out that the facts of environmental law can be visualized with the sustainability pyramid (Fig. 3), and only a comprehensive lifecycle assessment can show to which category a product belongs.

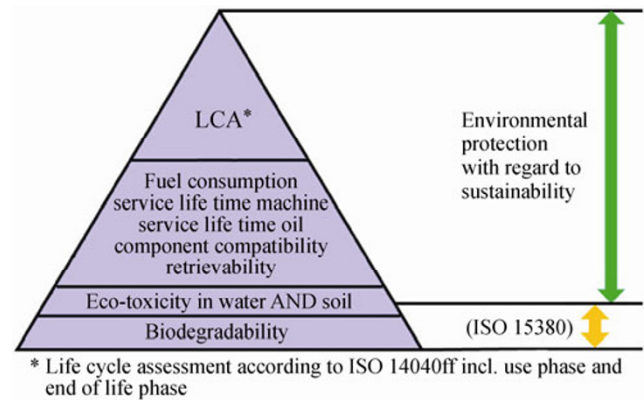


Fig. 3 Sustainability pyramid for hydraulic fluids [32].

3.3 Research on the tribological aspects of the natural ecological environment (including atmosphere, water, and soil, etc.) and natural disaster (including earthquake, landslide, mud-rock flow and volcanic eruption, etc.), which mainly focused on the role, mechanisms, and effects of friction

Xianshuihe fault located in the Tibetan plateau in China is a highly active strike-slip fault. To understand its historical seismicity characteristics and to obtain insight into its seismic potential, a numerical simulation of seismic activity was performed using a rate- and state-dependent friction law [33]. It was found that the cumulative distribution function of the recurrence intervals of simulated earthquakes at each segment approximately obeys a Brownian passage time distribution or a lognormal distribution.

Later on, using a rate-, state-, and temperature-dependent friction law, a numerical method was developed to investigate the effects of frictional heating and thermal advection on pre-seismic sliding [34].

Han and coworkers [35] investigated the ultra-low friction of carbonate faults caused by thermal decomposition. They demonstrated that thermal decomposition of calcite due to frictional heating induces pronounced fault weakening with steady-state friction coefficients as low as 0.06; moreover, this thermal decomposition may be an important process for the dynamic weakening of faults.

3.4 Tribological technologies for providing technological support to the equipment of both renewable and clean energy

Meeting future world energy needs while addressing

climate change requires deployment of various renewable and clean energies as alternatives to traditional fossil energy; examples include wind energy, solar energy, marine energy, nuclear energy, geothermal energy, and so on.

Frictional contacts in wind energy plants are found in gears and bearings. Due to severe operating conditions, the average lifetime of main bearings and multiplier gears is between 5–7 years in Western Europe and about 2–3 years in Asian countries [36]. REWITEC nanocoatings is a metal treatment that can be applied to gearboxes and bearings during regular operation for restoration of its efficiency and economy [37]. The documented tests and evaluations of gearbox operation were reviewed for the REWITEC technology. It has been proven that this technology was validated for improvement of operation in wind turbine gears. Taking specific areas with micro-pitting in the metal surfaces of a wind turbine gear before the application of REWITEC and after 6 months of treatment it was found that the surface damages are filled and the asperities smoothened, and thus the surfaces were smoother with higher surface contact area (Fig. 4).

Heemskerk [38] pointed out that wind turbines are complex dynamic systems that require advanced technologies (including tribology) to yield answers to service life and early failure issues. He suggested focusing on nine areas for tribology R&D applied to wind turbine rolling bearing.

A six-degree-of-freedom dynamic bearing model (DBM) has been used to simulate roller-raceway slip for a cylindrical roller bearing used in an intermediate shaft location of a wind turbine gearbox [37]. It was found that significant slip occurred during rapid transient accelerations and decelerations, but these high slip conditions decayed to a much lower level of slip at steady state. Moreover, extreme slip occurred for low load and high speed conditions because of concomitant contact area reduction and traction loss at the roller-raceway interfaces.

Based on a literature review related to the study of the phenomenon of micro-pitting in wind turbine gearbox roller bearings, a proposed test scheme could be created from which a method to predict the risk of micro-pitting might be determined [39].

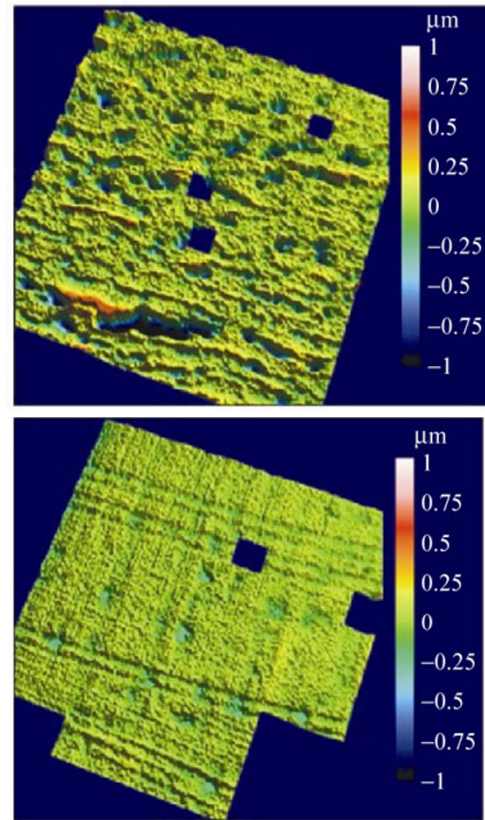


Fig. 4 Images in 3D for the metal surface before and after treatment with REWITEC with 6 months difference [36].

The tribology of three marine energy conversion devices, namely, offshore wind turbines, tidal turbines, and wave machines has been reviewed [40]. These devices are sensitive to operation and maintenance costs and thus rely on functioning tribological parts and lubrication.

4 Developing directions

Faced with a great number of tribological problems demanding prompt solution, which relate to the earth-scale environmental pollution and crisis of energy, green tribology should be extended in the following areas.

4.1 Large-scale deployment of existing knowledge, methods, and technologies of green tribology

More recently, three tribological case studies (micro Combined Heat and Power systems, slipways, recycled plastics) presented by Tzanakis and coworkers are the outstanding examples in this aspect [12].

4.2 Research and development of novel green tribological technologies

- (1) Low-carbon bio- and ecolubricants
 - Halogen-free and biodegradable oils
 - Carbon-neutral vegetable oils
- (2) Environmental-friendly tribological materials and coatings
 - Tribological applications of ecomaterials
 - Biological coatings applied on the surface of implants or medical devices
- (3) New tribo-techniques based on bionics

4.3 Making the traditional tribo-materials and lubricating materials “green” in the course of a lifecycle, namely, realizing cleaner production or ecodesign of the above materials

4.4 Research and development of tribo-techniques to support diversification and hybridization of renewable and clean energy

4.5 Building up the theory and methodology of green tribology

- (1) Setting up the theories and methods of analyses and evaluation of sustainability (including value of environmental and ecological impacts, value of saving energy, etc.) for tribological parts, tribo-systems, and tribo-techniques.
- (2) Research on the theories and methods of integration of different green tribological techniques, and of the effects of coupling and coordinating among various areas of green tribology.

5 Concluding remarks

Green tribology plays a unique role in developing a low-carbon economy, dealing with environmental pollution, the energy crisis, and climate change on a global scale. Therefore, it is one of the important ways forward to a sustainable society.

Just as Jost pointed out, “...the cause of Green Tribology is indeed a worthy cause for all tribologists and their organizations to pursue, as it will help tribology to play its rightful part, not only for the benefit of science and technology, but much more importantly, for the benefit of mankind...” [6].

Consequently, tribologists ought to dedicate their best efforts to the development and application of green tribology, thus adding valuable contributions to the existence and development of humanity.

In this paper, the definition, disciplinary features, objectives, mission, technological connotations, and the future developing directions of green tribology have been expounded comprehensively. These findings may contribute to laying the foundations for further advancement in green tribology.

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References

- [1] Zhang S W. Investigation concerning the developing directions of tribology in China (in Chinese). *Tribology* **21**: 321–323 (2001)
- [2] Zhang S W. Current industrial activities of tribology in China. *Plenary Lecture to the 5th China International Symposium on Tribology (CIST) 2008*, Beijing, 2008.
- [3] 30th Anniversary and “Green Tribology”—Report of a successful Chinese Mission to the United Kingdom (7th to 14th June 2009), Tribology Network of Institution of Engineering and Technology, 2009.
- [4] Zhang S W. Tribological application in China and green tribology. Institution of Engineering and Technology. London UK, 2009.
- [5] Jost H P. Green tribology—A footprint where economies

- and environment meet. *Address to the 4th World Tribology Congress*, Kyoto, 2009.
- [6] Jost H P. Development of green tribology—An overview. *Seminar—New Direction in Tribotechnology*, Moscow, 2010.
 - [7] Nasonovsky M, Bhushan B. Green Tribology. *Phil Trans R Soc A* **368**: 4675–4676 (2010)
 - [8] Nasonovsky M, Bhushan B. Towards the “Green Tribology”: Biomimetic surfaces, biodegradable lubrication, and renewable energy. In *Proceedings of STLE/ASME International Joint Tribology Conference*, San Francisco, 2010.
 - [9] Zhang S W. Green tribology—The way forward to a sustainable society. In *Proceedings of the International Tribology Congress—ASIATRIB 2010*, Perth, Australia, 2010: 6.
 - [10] Tzanakis I, Hadfield M, Thomas B, Noya S M, Henshaw I, Austen S. Future perspectives on sustainable tribology. *Renewable and Sustainable Energy Reviews* **16**: 4126–4140 (2012)
 - [11] Nasonovsky M, Bhushan B (Eds). *Green Tribology: Biomimetics, Energy Conservation and Sustainability*. Berlin: Springer, 2012.
 - [12] Assenova E, Majstrovic V, Vencel A, Kandeve M. Green tribology and quality of life. *International Journal of Advanced Quality* **40**: 1–6 (2012)
 - [13] Deitz T G. Advanced PAO based industrial lubricants for improved energy efficiency. In *Proceedings of the 4th World Tribology Congress*, Kyoto, 2009: 39.
 - [14] Hirao K, Yamada M, Kijiki T, Maekawa N. Environment and energy saving by use of synthetic esters. In *Proceedings of the 4th World Tribology Congress*. Kyoto, 2009: 38.
 - [15] Koyamaishi N, Murakami M, Komiya K, Moritani H. Study of future oil. In *Proceedings of the 4th World Tribology Congress*. Kyoto, 2009: 577.
 - [16] Matsuyama H, Kawaguchi K, Uemura A, Masuda N. Development of super-low friction torque tapered roller bearing for high efficiency axle differential. In *Proceedings of the 4th World Tribology Congress*, Kyoto, 2009: 591.
 - [17] Friedrich K, Almajid A A. Polymer composites in tribo-applications with elongated maintenance intervals and reduced energy consumption. In *Proc International Tribology Congress—ASIATRIB 2010*, Perth, Australia, 2010, K3.
 - [18] Ji L, Li H, Zhou F, Quan W, Chen J, Zhou H. Fullerene-like hydrogenated carbon films with super-low friction and wear, and low sensitivity to environment. *J Physics D: Applied Physics* **43**: 015404 (2010)
 - [19] Higdon C, Cook B, Harrings J, Russell A, Gddsmith J, Qu J, Blan P. Friction and wear mechanisms in AlMgB₁₄-TiB₂ nanocoatings. *Wear* **273**: 2111–2115 (2011)
 - [20] Puértolas J A, Martínez-Nogués V, Martínez-Morlanes M J, Mariscal M D, Medel F J, López-Santos C, Yubero F. Improved wear performance of ultra high molecular weight polyethylene coated with hydrogenated diamond like carbon. *Wear* **269**: 458–465 (2010)
 - [21] Numazaki R, Nakayama S, Inayama T, Nakayama S, Inayama T, Isogai Y, Minami I, Mori S. Contribution for energy saving by novel environmental lubricants containing derivatives from natural resource. In *Proceedings of the 4th World Tribology Congress*, Kyoto, 2009: 41.
 - [22] Sanchez R, Stringari G B, Franco J M, Valencia C, Gallegos C. Use of chitin, chitosan and acylated derivatives as thickener agents of vegetable oils for bio-lubricant applications. *Carbohydrate Polym* **85**: 705–714 (2011)
 - [23] Souza J C M, Henriques M, Oliveira R, Teughels W, Celis J-P, Rocha L A. Biofilms inducing ultra-low friction on Titanium. *J Dent Res* **89**: 1470 (2010)
 - [24] Klein J. Hydration lubrication: Exploring a new paradigm. In *Proceedings of the China 6th International Symposium on Tribology*, Lanzhou, China, 2011: 1–2.
 - [25] Shashidhara Y M, Jayaram S R. Vegetable oil as a potential cutting fluid—An evolution. *Tribol Int* **43**: 1073–1081 (2010)
 - [26] Winter M, Herfellner T, Malberg A, Eisner P, Dwuletzi H, Zein A, Bock R, Hermann C. Mineral oil free machine tool—the usage of ecologically benign lubricants as coolant and fluid. In *Proceeding of the 18th International Colloquium Tribology*, Stuttgart/Ostfildern, Germany, 2012: 143.
 - [27] Hirani H, Verma M. Tribological study of elastomeric bearings for marine propeller shaft system. *Tribology International* **42**: 378–390 (2009)
 - [28] Han Z, Zhang J, Ge C, Wen L, Lu R. Erosion resistance of bionic functional surfaces inspired from desert scorpions. *Langmuir* **28**: 2914–2921 (2012)
 - [29] Akay A, Giannini O, Massi F, Sestieri A. Disc brakes squeal characterization through simplified test rigs. *Mechanical Systems and Signal Processing* **23**: 2590–2607 (2009)
 - [30] Bartz W J. The green automobile—definition and realization. In *Proceedings of the China 6th International Symposium on Tribology*, Lanzhou, China, 2011: 73.
 - [31] Wani M F, Anand A. Life-cycle assessment modelling and life-cycle assessment evaluation of a triboelement. *Proc IMechE Part J: J Engineering Tribology* **224**: 1209–1220 (2010)
 - [32] Muller-Zermini B, Goule G. Environmental approach to hydraulic fluids. In *Proceeding of the 18th International Colloquium Tribology*, Stuttgart/Ostfildern, Germany, 2012.
 - [33] Kato N, Lei X, Wen X. A synthetic seismicity model for the Xianshuihe fault, southwestern China: simulation using a rate-dependent friction law. *Geophys J Int* **169**: 286–300 (2007)

- [34] de Lorenzo S, Lodds M. Effect of frictional heating and thermal and advection on pre-seismic sliding: a numerical simulation using a rate-, state- and temperature-dependent friction law. *J Geodynamics* **49**: 1–13 (2010)
- [35] Han R, Shimamoto T, Hiroset Ree J H, Ando J. Ultralow friction of carbonate faults caused by thermal decomposition. *Science* **316**: 878–881 (2007)
- [36] Bill S. BEWITEC surface technology-Reconditioning and durable wear protection for high loaded gearboxes and bearings in wind turbines. In *Proceedings of the 18th International Colloquium Tribology*, Stuttgart/Ostfildern, Germany, 2012.
- [37] Kang Y S, Evans R D, Doll G L. Roller-raceway slip simulations of wind turbine gearbox bearings using dynamic bearing model. In *Proceedings of STLE/ASME International Joint Tribology Conference*, San Francisco, USA, 2010: 407–409.
- [38] Heemskerk R S. Tribology for wind turbines: R&D needs to increase sustainability of the technology. In *Proceedings of the 37th Leeds—Lyon Symposium on Tribology*, Leeds, UK, 2010.
- [39] Harris T A, Kotzalas M N. Predicting micro-pitting occurrence in wind turbine gearbox roller bearings. In *Proceedings of STLE/ASME International Joint Tribology Conference*, San Francisco, 2010.
- [40] Wood B J K, Bahaj A S, Turnock S R, Wang L, Evans M. Tribological design constraints of marine renewable energy systems. *Philosophical Transactions of the Royal Society A* **368**: 4807–4827 (1929)



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